

# **SIMULTANEOUS ASSESSMENT OF PHOTOSYNTHETICALLY ACTIVE AND ULTRAVIOLET SOLAR RADIATION**

**A.V. Parisi<sup>\*‡</sup>, J.C.F. Wong<sup>†</sup>, C. Randall<sup>\*</sup>**

<sup>\*</sup>Centre for Astronomy and Atmospheric Research, Faculty of Sciences, University of Southern Queensland, TOOWOOMBA 4350 AUSTRALIA. Fax: 61 74 6312721. Email: [parisi@usq.edu.au](mailto:parisi@usq.edu.au)

<sup>†</sup>Centre for Medical and Health Physics, Queensland University of Technology, GPO Box 2434, BRISBANE 4001 AUSTRALIA.

<sup>‡</sup>To whom correspondence should be addressed.

## **Abstract**

A new dosimetric package for assessing solar radiation affecting photosynthesis in the visible and ultraviolet wavebands in plant canopies has been developed and tested. The package consists of several detectors sensitive to various wavebands between 290 and 700 nm. For photosynthetically active radiation (PAR), the dosimeter was calibrated for exposures in terms of photosynthetically active photons between 0.003 and 0.38 mol m<sup>-2</sup>. The package allows simultaneous assessment of the irradiances across the visible and ultraviolet wavebands. Over a plant canopy, the biologically effective ultraviolet radiation varied by approximately a factor of 2 compared to a variation by approximately a factor of 14 in the photosynthetic photon flux density.

**Keywords:** PAR, UV, ultraviolet, solar radiation, photosynthetically active radiation

## 1. INTRODUCTION

The solar visible waveband (400-700 nm) is essential for photosynthesis in plants. On the other hand, UV radiation, in particular, the UVB waveband (280-320 nm) can adversely affect plant growth and physiology (Teramura and Sullivan, 1994). In plant studies, it is necessary to quantify the exposure of various parts of the plant to the visible and ultraviolet wavebands of the solar spectrum. This and the fact that the UVB plant response is dependent on the level of exposure to solar visible radiation (Caldwell et al., 1995) highlights the necessity for assessment of the amount of radiation in the visible and UV wavebands that reaches plant surfaces. A spectroradiometer system (Wong et al., 1995) may be used to measure solar spectral irradiance with the results used to determine the biologically effective exposure of plants in particular wavelength ranges. The biologically effective exposure of solar radiation is the solar spectral irradiance weighted with a suitable action spectrum (Caldwell et al., 1986). However this method provides only the ambient exposure at the site of measurement. For plant canopies, such measurements only apply at the top of the canopy, before any leaf interception and reflection and consequent irradiance changes. These measurements cannot be employed to assess the exposure of particular plant parts, or at different locations in the canopy. Due to leaf angle, leaf reflectance, and shading of leaves by leaves higher in the canopy, and by neighbouring plants, exposure through the canopy differs significantly from the ambient exposure

An ultraviolet spectrum evaluator (Parisi et al., 1997) has been employed for measurement of the solar spectral irradiance and the result can be used to determine the

biologically effective UV incident on a plant canopy (Parisi et al., 1996). The spectral albedo of vegetation varies with wavelength (Feister and Grewe, 1995) and as a result the relative proportions of the UV and visible irradiances may vary at various levels of the plant. Additionally, the relative proportions of the diffuse to direct radiation varies across the UV and visible wavebands. Consequently, it is necessary to measure both the UV and visible irradiances in research of plant growth and physiology. Radiative transfer models have been developed for calculating the light penetration within a plant canopy (Anisimov and Fukshansky, 1992 and 1993), however, they cannot account for all the complex temporal and spatial variations of the visible and UV radiation environment within a plant canopy.

Photodiodes (Gutschick et al., 1985, Sassenrath-Cole, 1995) or meters Grant (1991) connected to computers or dataloggers have been employed to measure irradiances in plant canopies. These systems require ancillary electronic and computer equipment. Allen et al. (1993) have described a crystal violet doped cellulose triacetate film that may be employed as a dosimeter of visible radiation, however an exposure period of several days is required. Photographic film has been employed to monitor X-ray radiation (Fajardo et al., 1995) and diazo film has been investigated for UV dosimetry (Ali and Jacobson, 1980, Moseley et al., 1984). They can not provide information about the spectral irradiance. There is no system based on dosimeters for simultaneously measuring the PAR and the UV wavebands to the leaves of plants. This paper describes an innovative, reliable, portable and passive device employing two sets of sensors sensitive to the visible and UV wavelengths respectively for simultaneously measuring

the photosynthetically active radiation and the biologically effective ultraviolet radiation on and within a plant canopy. The system requires no expensive computer or electronic equipment and may be deployed for simultaneous measurements at multiple sites over a plant canopy.

## **2. MATERIALS AND METHODS**

### **2.1 Dosimeter**

The spectrum evaluator based on four dosimeter materials previously described (Parisi et al., 1997) was employed for evaluation of the biologically effective UV (UVBE) (shorter than 400 nm) calculated employing the plant damage action spectrum (Caldwell, 1971). The wavelength range of this device was extended into the PAR. The dosimeter for the visible waveband was based on 35 mm AGFA 25 APX photographic film. This material was selected as it is readily and inexpensively available commercially, simply processed, responsive to visible wavelengths and changes in the optical density of the film may be readily measured. The response of the film provided by the manufacturer shows that the film is responsive to wavelengths between 400 and approximately 665 nm. The film was cut into approximately 30 mm lengths in total darkness in the darkroom and placed in a holder constructed from black plastic to prevent any stray light leakage with an opening on the front of approximately 10 mm x 20 mm to allow exposure of the film. This opening was covered with a piece of cardboard to act as a shutter.

Filters were employed in order to increase the exposure time of the dosimeter. These were AGFA 25 APX photographic film that had been previously exposed and developed.

This film was exposed evenly across the entire length to ensure a uniform optical density. Two pieces of pre-exposed and processed film were employed as filters. The optical absorbance of these filters at 800 nm was more than 2.5 which is the upper limit of the dual beam spectrophotometer (Shimadzu, model UV-160, Kyoto, Japan) employed. The size of the prototype, in the form of a film badge, is 9 cm x 9 cm with a weight of 13 g. Once prepared the dosimeters were stored in a black plastic bag to prevent exposure. The size and weight of the prototype can be reduced in the next version.

Following exposure, the film was removed from the holders in total darkness in the darkroom and developed in Kodak D19 developer. The developing process was standardised for each batch of dosimeters with the developer maintained at 27°C and a developing time of 5 minutes. The other chemicals in the developing process were stop bath (0.5 min), fixer (2 min), water (5 min) and photoflo (1 min). Once dried the degree of darkening of the film was quantified by measuring the optical density of the dosimeter with the dual beam spectrophotometer. In order to establish the wavelength for measuring the absorbance, a scan of the absorbance was performed between 400 and 800 nm for a developed film that had been exposed and a piece of developed film that had not been exposed. The results (Figure 1) show that the largest absorbance change in the film occurs at 800 nm. Consequently, the absorbance at this wavelength will be employed to quantify the amount of darkening in the dosimeter due to exposure.

## **2.2 Dose Rate Independence**

The dose rate independence of the dosimeter was tested by exposure to irradiances of 55, 25 and 12 W m<sup>-2</sup> as measured with a calibrated spectroradiometer (Wong et al., 1995)

fitted with a photomultiplier tube sensitive to the visible wavelengths (Hamamatsu model R928) and a 15 cm diameter integrating sphere (model OL IS-640, Optronics Laboratories, USA). Exposure periods of 128, 256 and 512 seconds respectively were employed to provide the same total exposure. The light source employed was a quartz tungsten iodide (QI) lamp in a dark room. Following exposure, each film in the dosimeter was developed and the absorbance at 800 nm measured.

### **2.3 Reproducibility, Temperature and Cosine Response**

The application of the dosimeter depends on the reproducibility of the darkening of the film for a given exposure. This was tested by exposing six dosimeters for 10 min to the QI lamp at a distance of 1 m. For the temperature response the dosimeter was exposed at temperatures between 24.6 and 42.4 °C for 10 minutes to the QI lamp at a distance of 50 cm. Similarly, for the cosine response, each dosimeter was exposed for 10 minutes to the QI lamp at 50 cm while rotating the light source in 10 degree increments between angles of 0 and 60 degrees to the vertical while maintaining the set distance above the dosimeter.

### **2.4 Calibration**

The dosimeter was calibrated by exposing on a horizontal surface, five film/filter combinations for exposure periods of between 2 and 240 seconds and measuring the visible spectral irradiance in one nanometre increments with the calibrated spectroradiometer. The photosynthetically active radiation was expressed in terms of the photosynthetic photon flux density (P) expressed as (McCree, 1981):

$$P = 8.35 \times 10^{-9} \int_{400}^{700} \lambda S(\lambda) d\lambda \quad \mu\text{mol m}^{-2} \text{ s}^{-1} \quad (1)$$

where  $S(\lambda)$  is the incident spectral irradiance in  $\mu\text{W m}^{-2} \text{ nm}^{-1}$  and  $\lambda$  is the wavelength in nanometres. The time integrated exposures over a period,  $t$ , were calculated in terms of photosynthetically active photons (A) (CIE, 1993) as follows:

$$A = t * P * 1 \times 10^{-6} \quad \text{mol m}^{-2} \quad (2)$$

This calibration was undertaken on 10 November, 1997 at 10:20 Australian Eastern Standard Time (EST) and repeated for different solar spectra on 12 November, 1997 at 10:00 EST and 11:05 EST. The calibration was validated by employing simultaneous measurements of the photosynthetically active photons with the spectroradiometer and the detector for exposure periods between 10 and 240 seconds.

## 2.4 Irradiance Measurements on Plants

The dosimeter system was applied to measure the biologically effective UV and the photosynthetic photon flux density on a potted plant (Petunia sp. Hybrid) in Toowoomba (27.5 °S latitude), Queensland, Australia. The measurements were undertaken at 12:10 EST on 21 August with a solar zenith angle of approximately 40°. The cloud cover as measured by a trained Bureau of Meteorology observer was 1 and 7 octa at 9:00 and 15:00 EST respectively. The canopy of the plant was approximated by a hemisphere (Parisi and Wong, 1994) and five dosimeters were deployed over the plant at the inclinations and orientations provided in Table 2, namely, the top of the plant on a



horizontal plane and orientated to the north, east, south and west at an inclination of 45 degrees to the horizontal. The dosimeters were deployed on a lightweight frame constructed from 2 mm steel (Figure 2). Employing the lightweight frame prevented any changes in the angle and position of the leaves. The UV spectrum evaluator was exposed for 15 minutes and the dosimeters for the PAR radiation exposed for 60 seconds.

### **3. RESULTS**

#### **3.1 Dose Rate Independence**

The absorbance for the same total exposure for three different dose rates is provided in Figure 3. The absorbance of the exposed dosimeters agrees to better than 6% for the different dose rates providing the same total exposure.

#### **3.2 Dark Reaction**

The application of the dosimeter depends on the stability with time of the film after developing. Four dosimeters were exposed to the QI lamp for exposure periods between 64 and 512 seconds, developed and their absorbances at 800 nm measured immediately after developing. The dosimeters were stored in the dark and the absorbances after periods of one and seven days were within one to two percent of these values. Consequently, the developed dosimeter is stable with time.

#### **3.3 Reproducibility, Temperature and Cosine Response**

The results of exposing six of the dosimeters to the same exposure produced absorbances with a standard deviation less than 2% of the mean. The results of the temperature response are provided in Figure 4(a) with no temperature effect over the range

investigated. The cosine response of the dosimeter is provided in Figure 4(b) with the solid line representing the ideal cosine response. The largest difference between the experimental data and the ideal response occurs at an angle of  $60^\circ$  to the vertical with a difference of 21%. For the smaller angles, the agreement is 13% or better. The angles greater than  $60^\circ$  were not measured as the exposure time of 10 minutes was not sufficiently long for the film in the dosimeter to darken.

### **3.4 Calibration**

The calibration of the dosimeter for the visible waveband is provided in Figure 5 and includes the three sets of data from the three calibration times. The y-axis is the time integrated exposure and reported as the exposure to photosynthetically active photons (A) in units of  $\text{mol m}^{-2}$  and calculated according to Equations (1) and (2). A quadratic has been fitted with an R-squared of 0.997. The calibration data was from two days at three different times of the day with resultant different solar spectra with different amplitudes of spectral irradiances. Any variation in the solar spectrum does not produce a significant change in the calibration. For the validation experiment, the photosynthetically active photons measured with the calibrated spectroradiometer and the detector are provided in Table 1 and the differences averaged to 15% with a range of 7 to 24%.

### **3.5 Irradiance Measurements on Plants**

The biologically effective UV and the photosynthetic photon flux density to the Top, N, E, S and W sites on the plant canopy on 21 August at 12:10 EST are provided in Table 2. The UVBE ranges from 89 to  $174 \text{ mW m}^{-2}$  for the S and N sites respectively. In comparison, the photosynthetic photon flux density ranges from 151 to  $2051 \mu\text{mol m}^{-2} \text{s}^{-1}$ .

The ratio of the UVBE to each site compared to UVBE to the top site ranges from 0.9 to 1.8 compared to the same ratio for P that ranges from 0.1 to 1.4. The main contributing factor to these differences between UVBE and P is predominantly the higher proportion of the diffuse radiation relative to the direct component in the UV waveband compared to the visible waveband. This is even more pronounced on the partially cloudy day of the exposure when the diffuse component of the UV waveband would have been higher as a result of the cloud. As a result, the photosynthetic photon flux density varies more over the plant canopy than the UVBE does.

#### **4. DISCUSSION**

A new dosimetric package for assessing solar radiation affecting photosynthesis in the visible and ultraviolet wavebands has been tested and applied for the measurement of the photosynthetic photon flux density and biologically effective ultraviolet radiation at various sites over a plant canopy. The advantage of the dosimeter over conventional methods is that it is a passive system that requires no computer or other electronics or expensive equipment to measure the PAR at multiple sites simultaneously over a plant canopy. This cannot be achieved with conventional systems. Additionally, the new detector can provide data on photosynthetically active exposures along with simultaneously providing information about UV exposures. In terms of photosynthetically active photons, the dosimeter has a reasonable dynamic range and was calibrated for exposures between 0.003 and 0.38 mol m<sup>-2</sup>. The size of 9 cm x 9 cm can be reduced in the next prototype of the dosimeter. The error in the detector due to sources such as timing of the exposure, calibration and development could contribute to an overall error of 20%. At the time of the exposure, the biologically effective UV varied by

approximately a factor of 2 over the plant canopy compared to the photosynthetic photon flux density that varied by approximately a factor of 14.

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Table 1 - Results of the validation experiment comparing the photosynthetically active photons measured with a calibrated spectroradiometer and the detector.

Exposure period (secs)	A (mol m <sup>-2</sup> )	
	Spectroradiometer	Detector
10	0.035	0.028
30	0.10	0.09
60	0.21	0.16
240	0.84	0.78

Table 2 - The biologically effective UV and the photosynthetic photon flux density to each site on the plant canopy at 12:10 EST on 21 August, 1997 where  $\alpha$  is the inclination angle relative to the horizontal. The UV dosimeter system was exposed for 15 minutes and the PAR dosimeter for 60 seconds.

Date	Site	$\alpha$ ( $^{\circ}$ )	UVBE ( $\text{mW m}^{-2}$ )	UVBE Ratio Top/site	P ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	P Ratio Top/site
21 Aug	Top	0	98	1.0	1440	1.0
	N	45	174	1.8	2051	1.4
	E	45	126	1.3	151	0.1
	S	45	89	0.9	153	0.1
	W	45	99	1.0	988	0.7

## FIGURE CAPTIONS

Figure 1 - Scan of the optical absorbance of an unexposed (-----) and exposed (——) PAR dosimeter.

Figure 2 - Plants with the system of dosimeters deployed over the approximate shape of the plant canopy.

Figure 3 - Absorbance at 800 nm for the same total exposure at three different dose rates.

Figure 4 - (a) The temperature response and (b) the cosine response of the PAR dosimeter.

Figure 5 - Calibration of the PAR dosimeter for photosynthetically active photons (A).

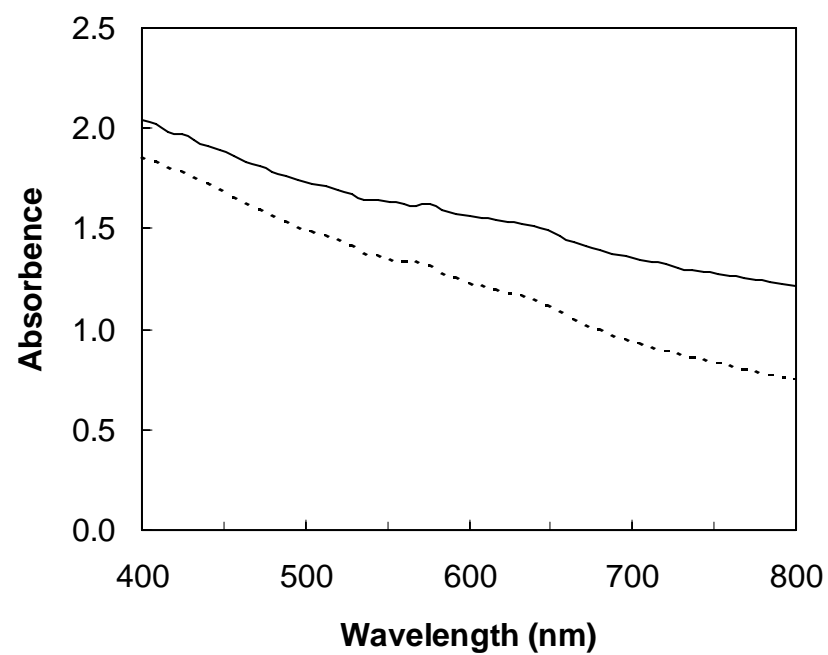


Figure 1

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Figure 2

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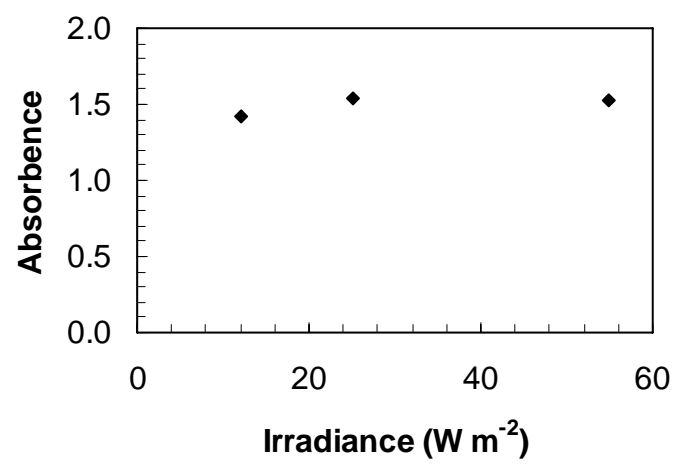


Figure 3

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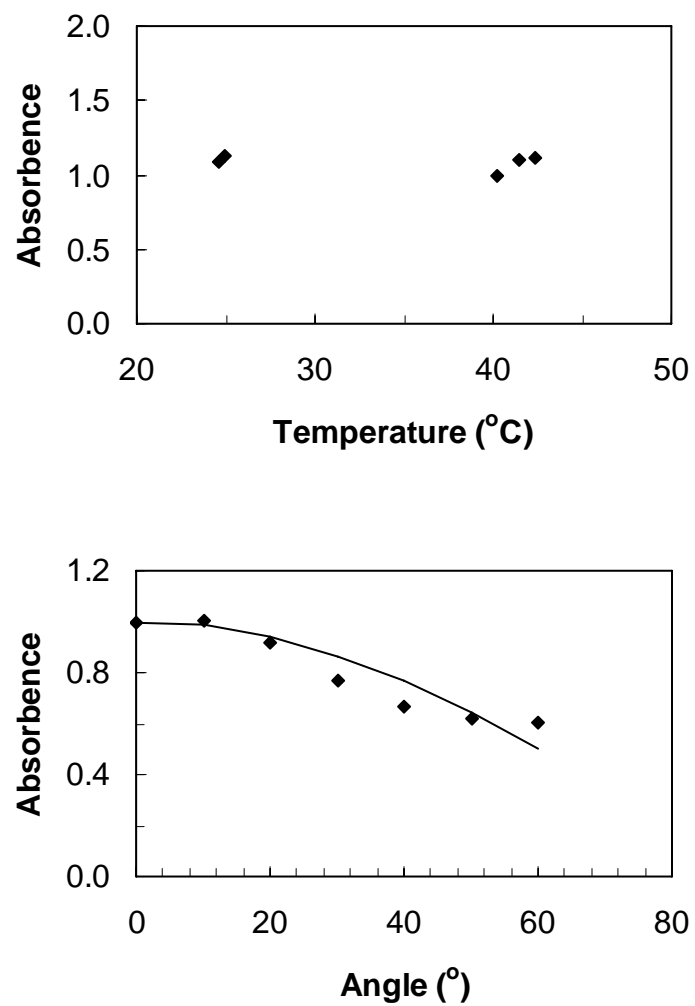


Figure 4

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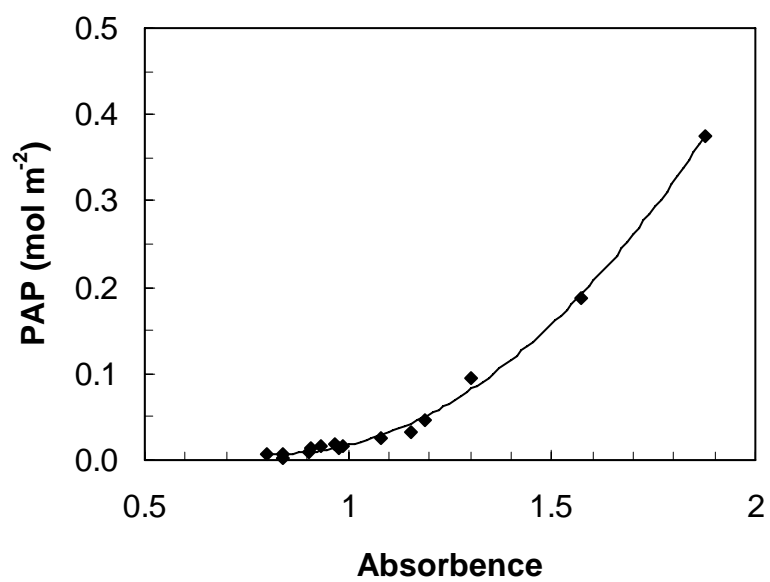


Figure 5

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